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Experimental Study of the Causes of the Fishhook Effect in a Mini-Hydrocyclone

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Abstract

The mini sized hydrocyclone is being proposed as a novel apparatus in complex micro-devices for in-line particle separation as it has a concise geometry and no moving parts. In this work, we present an experimental study on the causes of the fishhook effect for fine particle separation in a 5 mm mini-hydrocyclone. The fishhook effect denotes the shape of the separation efficiency curve having a fishhook-shaped curve in the fine particle range. The causes for the fishhook effect can be attributed to entrainment in the wake flow, reduction of drag force and change in the resultant force direction for the fine particles. The fishhook effect was found to be more pronounced for higher inlet velocities and for samples with relatively more coarse particles. The pronounced fishhook effect was explained by the enhancement of particle entrainment and an increase in the drag force reduction.

Introduction

Small hydrocyclone operation and the fishhook effect

There has been a rapid growth in the application of hydrocyclones in the chemical and mineral industries in the last 50 years. A typical hydrocyclone (figure 1) consists of a cylindrical body with a central tube (vortex finder) and a conical body with an underflow orifice. The particle-laden fluid is injected tangentially through the feed inlet, giving rise to outer and inner swirling flows and generating centrifugal force within the device. This centrifugal force field brings about a rapid classification of particles based on size difference. The classification performance can be expressed by a separation efficiency $\varphi(d)$, defined as:

$$\varphi(d) = \frac{u(d)}{o(d) + u(d)} \qquad (1)$$

where $u(d)$ is the mass of a specific sized particle, d, collected in the coarse product stream (hydrocyclone underflow), and $o(d)$ the mass of a specific sized particle collected in the fine product stream (hydrocyclone overflow). The particle size at which 50% efficiency occurs is defined as the cut size, d_{50}, and a smaller cut size represents the ability to separate finer particles [14].

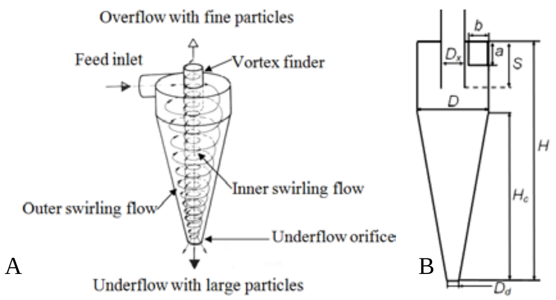

Figure 1. (A) A typical hydrocyclone configuration and flow pattern [14]; (B) Schematic of a hydrocyclone with the characteristic dimensions in the vertical plane [20].

A previous study has shown that the cut-size decreases with decreasing hydrocyclone diameter [6]; thus mini-sized hydrocyclones with small diameters are promising tools for classifying fine particles. With a concise geometry and no moving parts, the mini hydrocyclone is also being proposed as a novel apparatus in complex micro-devices for in-line particle separation.

For particle separation, an effective separation means the fine particles are separated to the overflow with high efficiency whereby the separation efficiency curve decreases monotonically with particle size**.** However, experimental evidence has suggested that the separation efficiency of very fine particles to the hydrocyclone underflow increases with decreasing particle size below a particle size of 10 µm [4, 7, 11]**.** This phenomenon is known as the fishhook effect and it interferes with the separation efficiency of fine particles resulting in poor separation. Several studies have shown that the fishhook effect originates from the hydrodynamic interaction of particles of different sizes, where fine particles are entrained by large ones for poly-dispersed suspensions [3, 11, 12]. However, the details of the fishhook effect mechanism are far from complete.

Wake flow effect and drag force reduction

The separation in a mini-hydrocyclone is a centrifugal sedimentation process. For dilute particle sedimentation and fluidization, a considerable amount of research [5, 10, 17] has shown that particle interaction occurs in the presence of a wake flow, which consequently leads to a drag force reduction for particles affected by the wake. The wake effect has been reported for Reynolds numbers as low as 0.06 for pairs of spheres falling in viscous flows [13]. The drag force on the upper sphere was found to be less than that on the lower sphere. Consequently, the velocity and acceleration for the upper sphere were larger than the corresponding values for the lower sphere. Jayaweera *et al.* [8] showed that for $Re>4$, the upper particle can be accelerated even if the two particles are ten diameters apart. Kaye and Boardman [9] conducted sedimentation experiment for a column filled with liquid paraffin and glass beads. They found that groups of particles fall faster than individual particles at particle volume concentrations ranging from 0.1 to 3 % showing that the drag forces on the particles have been reduced.

However, due to the flow complexity, exact measurements of the drag force reduction are difficult to conduct. Instead, a number of researchers have investigated the drag force reduction for interactive particles; that is, two fixed equi-sized particles usually arranged in the streamwise direction. For the interacting particles, the forward particle is termed the leading particle, whilst the backward particle is termed the trailing particle. The particle Reynolds number Re_1 is based on the free stream velocity and leading particle diameter.

Tsuji *et al.* [15] conducted unsteady three-dimensional simulation of the interactions between a uniform flow and two interacting particles. The drag force on the interacting particles was attenuated when the particles were aligned in the streamwise direction. For Re_1 = 250, and an inter-particle distance l of l = 0.1d, the drag force of the trailing particle was reduced to 7% of that experienced by a single particle. From l = 0.1d and 0.5d, the pressure contours show that the trailing particle is captured by the lower pressure region behind the leading particle. At l = 0.5d, Tsuji *et al.* [15] found that the separated flow from the leading particle did not engulf the trailing particle, but it is suppressed and makes ring-like vortices region between particles. The velocity vector plot shows the fluid moves in a relatively slow manner. These nearly stagnant and slow moving vortical flows between particles decrease the frictional drag of the trailing particle significantly, and result in the large attenuation of the total drag. As l increases to 2d, the trailing particle is outside the lower pressure region of the leading particle. However, the higher-pressure region, which was expected to occur in front of the trailing particle, does not exist under the influence of the leading particle. The obstruction to the formation of a high-pressure region reduces the streamwise pressure gradient, and results in the reduction of form drag. These observations are in agreement with experiments by Chen and Lu [2] and Zhu *et al.* [18].

Baz-Rodríguez *et al.* [1] studied the influence of the leading particle Reynolds number, Re_1, on drag force reduction. The total hydrodynamic force on the trailing particle, F_{HD}, is defined as

$$F_{HD} = F_{D2} + F_1 \quad (2)$$

where F_{D2} represents the quasi-steady drag on the trailing sphere, and F_1 is the convective inertial force due to axial non-uniformity of the wake flow, which includes the contributions of the acceleration fluid force and the added mass force. The drag force reduction increases with increasing Re_1. The results were explained by an increase of momentum dissipation in the wake flow, as the numerical results showed that the velocity deficit in the wake increases with increasing Re_1. Therefore, the average velocity around the trailing particle is smaller resulting in significant reduction of the drag force. On the other hand, due to a higher convective acceleration in the wake, the contribution of convective inertial force, F_1, are also found to increase slightly as Re_1 increases. However, the increase of the convective inertial force, F_1, is insufficient to compensate for the total drag force reduction. Although the interaction of two interactive particles is a special case, in general, the hydrodynamic force changes in the wake flow do provide insights into understanding the particle interaction mechanism.

In this work, we present experimental results on the investigation of the causes of the fishhook effect with a 5 mm mini-hydrocyclone. The influences of the inlet velocity and particle size distribution were investigated. The occurrence of the fishhook effect is attributed to the particle entrainment in the wake and the drag force reduction for the fine particles.

Experimental method

The dimensions of the 5 mm diameter mini-hydrocyclone used are given in Table 1 and was manufactured by micro-end milling. The two outlets were connected to relatively large pipes (6 mm diameter) enabling easy drainage of the outlet streams and minimal interference through pressure drops to the operation of the mini-hydrocyclone. The solid feed material was silica particles milled from beach sand having a density of 2.6 g/cm^3. The particle size distributions by volume for different sieved samples are shown in figure 2. The 60-µm sample, with 90% of particles less than 60 µm, was obtained by crushing the feed in a ball mill for 20 min and screening to pass a 75-µm sieve. The 18-µm sample with 90% of particles less than 18 µm required 7 hours of ball-milling. The 1:1 sample is a 1:1 volume mixture of the 18-µm and 60-µm samples; the 1:2 sample is a 1:2 volume mixture of the 18-µm and 60-µm samples.

Geometrical properties	Dimensions (mm)
Diameter, D	5.00
Total height, H	16.82
Conical section height, H_c	11.82
Overflow diameter, D_x	1.67
Vortex finder length, S	3.34
Inlet dimensions, $a \times b$	1.67×1.34
Underflow diameter, D_d	0.84

Table 1. Dimensions of the mini-hydrocyclone, as per the characteristic dimensions defined in Figure 1.

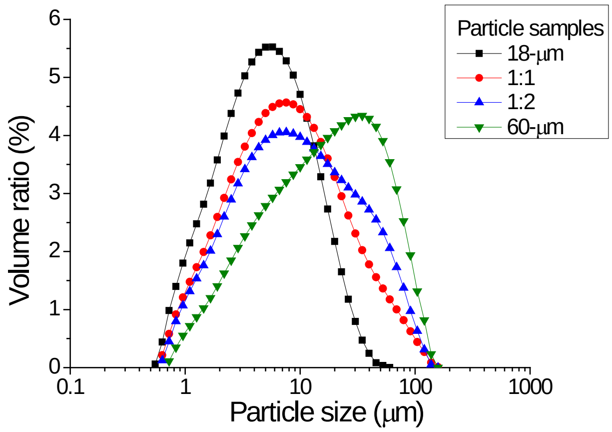

Figure 2. Particle size distributions of the silica samples.

The setup for the feed stream to the mini-hydrocycylone consisted of a magnetic pump linked to a sealed displacement bottle setup enabled particle wear on the pump head to be avoided. The flow rates were controlled by adjusting the pumping speed. A magnetic rotor in the bottle, activated by a magnetic stirring plate, ensured that the particles stayed evenly dispersed. The solids concentration was 5 g sand/L. Fifty ml timed samples were taken simultaneously from the two outlet streams during a run. The sample streams were then dried to determine the solids concentration of the overflow and underflow. The size distribution of each stream was analysed using a Malvern Mastersizer 2000 particle size analyser capable of detecting particles in the size range of 0.02 to 2000 µm. The particle separation experiments for each inlet velocity were repeated at least three times to check the repeatability and the results were averaged to give the separation efficiency curves.

Results and discussion

Effect of inlet velocity

The experimental separation efficiency curves for the 60-µm sample are shown in figure 3. The results demonstrate that a finer cut size, d_{50}, is obtained for a higher inlet velocity. This improvement in the separation can be explained by the change in flow characteristics at higher inlet velocities, *i.e.*, an increase in the tangential velocity, the expansion of the locus of the zero axial velocity vectors (LZVV) towards the cyclone wall and the underflow orifice, and the extension of the recirculating flow region. Further details of the mechanism can be found in our previous numerical study [20] of an identical mini-hydrocyclone.

For the 60-µm particle sample, which has a large fraction of coarse particles, the results show that the fishhook effect is observed for all inlet velocities from 0.4 to 4.0 m/s. Based on the experimental results and theoretical analysis, the mechanism of the fishhook effect is as follows:

1. Fine particles close to a large particle can be captured in the wake of the larger particle and be transported at the same velocity as the wake, which is slower than the free stream velocity.
2. As indicated by Tsuji *et al.* [15], the slow moving vortical structures in the wake flow reduce the friction drag on the fine particle, and result in the reduction of the total drag. In addition, a higher-pressure region that was expected to occur in front of the fine particles may not exist under the influence of the large leading particle. The obstruction to the formation of a high-pressure region reduces the streamwise pressure gradient, leading to the reduction of form drag.
3. A previous study [14] suggests that the major forces acting on the particles are the centrifugal force directed to the cyclone wall, and the flow drag force directed towards the cyclone centre region. The reduction in the drag force on the fine particles means that the resultant force would be directed towards the wall instead of cyclone centre leading to the observed fishhook effect.

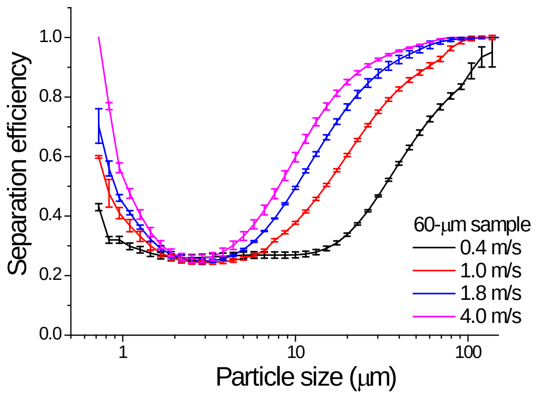

Figure 3. Separation efficiency curves with their standard deviations for four inlet velocities.

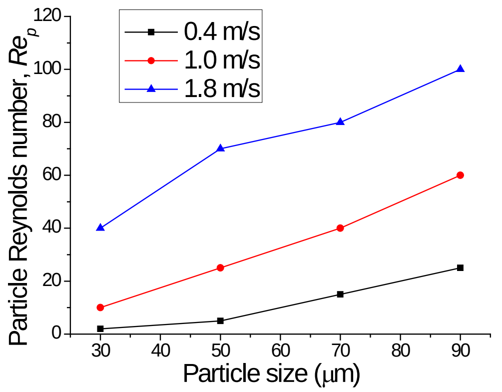

Figure 4. Simulation results of Re_p for three inlet velocities [20].

In addition, the experimental results show that a higher inlet velocity leads to a more pronounced fishhook effect. For example, the maximum separation efficiency in the fishhook region is around 0.4 for the 0.4 m/s inlet velocity case, and increases to 1.0 for the 4.0 m/s case. The difference can be explained by the variation in the particle Reynolds number, Re_p, for different inlet velocities. Fig. 4 presents the simulation of Re_p, for relatively coarse particles of 30, 50, 70, 90 µm from our previous numerical study [20] for an identical mini-hydrocyclone. For the 0.4 m/s case, the Re_p is small, *e.g.* Re_p = 20 for the 90 µm particle. At these Reynolds numbers, particles below or around 90 µm can only entrain a small fraction of fine particles as they have a small wake, resulting in minimal fishhook effect. In contrast, the higher inlet velocities give rise to larger particle Reynolds numbers, *e.g.* Re_p = 100 for 90 µm particle for the 1.8 m/s case. The Re_p for the 4.0 m/s case is expected to be even larger. Larger Re_p*'s* indicate that larger wake structures will develop which in turn, will entrain more fine particles behind the coarse ones. This hypothesis is supported by the study of Yao *et al.* [16]. They showed that solid particle dispersion/entrainment in the wake of a cylinder increases as the flow Reynolds number increased from 30 to 300. In particular, a sharp increase in entrainment occurs at $Re=50$ when vortex shedding begins in the wake flow. The enhancement of dispersion/entrainment was explained by the increase in the oscillation and amplitude of the wake flow with increasing *Re*, which can engulf and entrain more particles.

Another mechanism for the more pronounced fishhook effect for a higher inlet velocity could be due to the increased drag force reduction at higher particle Reynolds numbers. According to Baz-Rodríguez *et al.* [1], at higher Reynolds numbers, the shielding exerted by the coarse particle on the smaller particle is larger resulting in a correspondingly larger velocity defect in the wake. The average velocity on the fine particles is slower resulting in a larger reduction of the drag force and increased fishhook effect.

Effect of particle size distribution

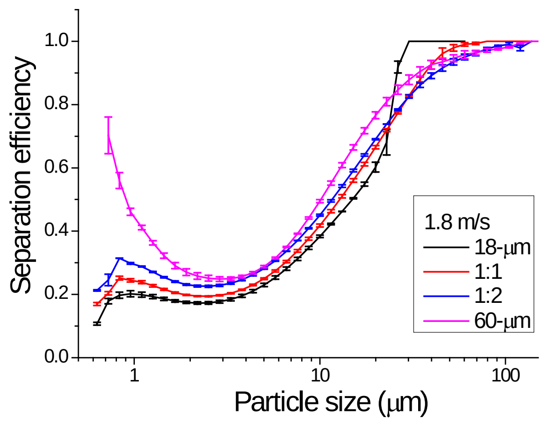

Figure 5. Separation efficiency curves with their standard deviations for four particle samples at the inlet velocity of 1.8 m/s.

The separation efficiency curves for the different particle samples having an inlet velocity of 1.8 m/s are shown in figure 5. The fishhook effect curve is barely noticeable for the 18-µm sample; the separation curve shows a nearly monotonic decrease of the separation efficiency with decreasing particle size. For the same mini-hydrocyclone, a computational study by Zhu *et al.* [19] shows that the onset of turbulent flow starts with an inlet velocity of 0.4 m/s and higher because of centrifugal instabilities. Therefore, the absence of the fishhook effect for the 18-µm sample suggests that the presence of turbulence in the flow may not be the direct cause of the fishhook effect. Figure 5 does show that an increasing amount of large particles leads to a more distinct fishhook effect. The variation of the fishhook effect for different sample groups is consistent with the study by Schubert [12], which shows that increasing the number of large particles in the feed leads to a more pronounced fishhook effect.

The barely noticeable fishhook effect for the 18-µm sample can be explained by the reduced entrainment by large particles. For this particle sample, a considerable amount of particles are present in fine range, in contrast to a minimal amount of particles in the coarse range; the largest particle is less than 60 μm. Consequently, the ratio of large to fine particle is smaller. With much less large particles in the flow, the regions influenced by large particles are minimal. Therefore, most of the fine particles are unaffected and their separation is due mainly to the centrifugal force exerted on them.

The intermediate size samples of 1:1 and 1:2 have a large proportion of particles in the intermediate size range. Therefore, the particles Reynolds numbers are only slightly larger than those of the fine particles. In turn, their influence on the finer particles is smaller and this leads to a smaller fishhook effect.

Conclusions

In this work, we present an experimental study on a 5 mm diameter mini-hydrocyclone to investigate the causes of the fishhook effect in fine particle separation.

For a 60-μm particle sample, the results show that the fishhook effect is observed for all inlet velocity cases from 0.4 to 4.0 m/s. The causes for the fishhook effect are attributed to the entrainment in the wake flow, reduction of drag force and change in the resultant force direction for the fine particles.

In addition, the experimental results show that a higher inlet velocity leads to a more distinct fishhook effect. This phenomenon can be explained by the enhancement of entrainment and an increase in the drag force reduction with increased particle Reynolds number, Re_p.

For the same inlet velocity, the separation efficiency for different particle samples was also investigated. The fishhook effect curve is barely noticeable for the 18-μm sample and this can be explained by the reduced entrainment from large particles. For the intermediate size samples of 1:1 and 1:2, the fishhook effect is relatively low as the large particle Reynolds numbers are slightly larger leading to only a small increase in fine particle entrainment.

The fishhook effect leads to poor separation of the fine particles. Our results suggest that it could be suppressed either by using a smaller inlet velocity or screening the sample to remove the larger particles which may necessitate the use of multiple mini-hydrocyclones optimised for different size ranges. More operational parameters including particle concentrations and sphericities need to be explored in future studies in order to thoroughly understand the fishhook effect.

Acknowledgments

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